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"Report developed under SBIR contract for topic A04-022."
The X-ray Imaging Module (XIM) is a compact, efficient, inexpensive imager component that can be ganged with other XIMs to produce very high spatial resolution seamless images over very large areas, over 2 meters in a single dimension, if necessary. XIM provides fast, deep-dynamic range, low-noise calibrated digital readouts at a user-selectable/motion-coordinated rate, enabling virtually all reconstructive imaging applications, such as CT, TDI, and laminography at energies of 2 MeV. In phase I, we built and tested a single prototype XIM unit at 2 MeV using the high energy x-ray source available at the Picatinny Arsenal. We proved a stitching approach that allows the construction of a single seamless very large image from multiple, smaller, slightly-overlapping images. We provided a multi-XIM unit that can image a region as large as 12 x 48 or 20 x 24 inches at high spatial resolution. A one-dimensional grid scatter-rejection scheme that will eventually reduce scattering at high energies was tested. In phase II, Skiametrics will build provide an erector-set multi-configuration 4-XIM unit, allowing very large areas, e.g., 12 x 48 inches or 20 x 24 inches, to be imaged at very high spatial resolution.

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X-ray MegaVolt Digital Imaging Inspection System

by

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Final Report

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Executive Summary

The X-ray Imaging Module (XIM) is a compact, efficient, inexpensive imager component that can be ganged with other XIMs to produce very high spatial resolution seamless images over very large areas, over 2 meters in a single dimension, if necessary. XIM provides fast, deep-dynamic range, low-noise calibrated digital readouts at a user-selectable/motion-coordinated rate, enabling virtually all reconstructive imaging applications, such as CT, TDI, and laminography at energies of 2 MeV. In phase I, we built and tested a single prototype XIM unit at 2 MeV using the high energy x-ray source available at the Picatinny Arsenal. Most importantly, we proved a stitching approach that allows the construction of a single seamless very large image from multiple, smaller, slightly-overlapping images. We also developed a conceptual design that can image a region as large as 12 x 48 or 20 x 24 inches at high spatial resolution. We have begun work on a one-dimensional grid scatter-rejection scheme that we hope will eventually lead to reduced scattering at high energies, though initial results were not promising.

In our program plan for phase II, Skiametrics will design and build a complete 4-XIM module, provide an erector-set multi-configuration x-ray imager unit, allowing very large areas, e.g., 12 x 48 inches or 20 x 24 inches, to be imaged at very high spatial resolution. The multi-XIM unit will be delivered and assembled at the Picatinny 2 MeV x-ray facility. Skiametrics will test, calibrate, and acquire quantitative x-ray images, and provide complete hardware, software and procedures for at least one high energy x-ray reconstructive imaging application, e.g., cone-beam CT. ***We expect the resulting cone-beam CT image set to have the highest resolution and lowest noise ever seen at MeV energies.***

B. Results of the Phase I Work

The X-ray Imaging Module (XIM) is a compact, efficient, inexpensive imager component that can be ganged with other XIMs to produce very high spatial resolution seamless images over very large areas, over 2 meters in a single dimension, if necessary. XIM provides fast, deep-dynamic range, low-noise calibrated digital readouts at a user-selectable/motion-coordinated rate, enabling virtually all reconstructive imaging applications, such as CT, TDI, and laminography.

XIMs are easily constructed from existing components and subsystems and do not require any exotic technologies. Even at high x-ray energies, XIMs are radiation resistant.

Summary of results

In phase I of the XIM SBIR program, Skiametrics designed and built one XIM module and has experimentally demonstrated:

- edge-to-edge sensitivity on the imaging
- the ability to seamlessly stitch together sub-images produced by individual XIMs, thereby enabling very large fields-of-view to be seamlessly integrated
- the usual x-ray imaging characteristics

Altogether, these demonstrations points validate the entire XIM-ganging concept.

We have also provided a software specification for use of XIM with a standard application interface, e.g., LabView/MatLab. In the (pending) option program we addresses developing an initial set of *generally* configurable tools for reconstructive imaging and will demonstrate one such application.

Our approach emphasizes astute calibration techniques, tested algorithms, and lack of dependence on a single technology or provider.

The details

The program was divided into 6 main tasks, including:

B.1. Technical specifications for a new x-ray imager

Technical specifications for a new x-ray imager were developed in the first month of the program. We divide these into specimen-based requirements and instrument-based requirements.

The specimen-based requirements include, most importantly, the ability to image the army's largest rounds – 155 mm ammunition. This also requires the use of 2-4 MeV x-rays, which will be available from the linac unit at Picatinny. What is NOT required is higher energy x-rays, e.g., 15 MeV, which we had originally proposed as part of testing the XIM unit in the option program. The changed requirements to our option program, will now include a high-resolution cone-beam CT imagery of a 155 mm round.

Critical instrument-based requirements include:

1. A field-of-view of the XIM that will accommodate the 155 mm round

2. A low-scatter geometry
3. Four lp/mm optical resolution at the conversion screen. Note that we do not expect to be able to be able to obtain x-ray resolutions at 4 lp/mm with high MTF in that region, if we can get scatter down to an acceptable level, we may be able to provide some sensitivity there. We would not use 4 lp/mm at full-scale imaging of the 155 mm round routinely because this would result in a reconstruction field of 1200 resolution elements across the field, and as many as 3600 vertically (and poor contrast) and an unacceptably high data acquisition times.
4. In addition, the dynamic range should be 12 bits or higher if possible.

B.2. The design of the x-ray imager module [XIM] prototype

A complete design of a prototype XIM was accomplished. Through much experience we have arrived at a basic configuration for x-ray imagers operating in the energy regime above 200 keV. The basic configuration is a two-mirror design as shown in Figure 1. The main advantage of such a design is that the detector always faces the rear, and there is no direct path into the lens or CCD from any primary beam interaction center. Thus, background is low, and any scattered x-rays involve very low energies and/or are multiply scattered. With such an arrangement, the backscatter is always close to 180 degrees, and even at the highest x-ray energies, the maximum energy of the scattered x-rays is always less than 500 keV. Thus, a leaded glass can be inserted between the second-fold mirror and the lens, and it will stop virtually all of the backscattered flux. A single-fold mirror system would require a much thicker leaded glass, because the scattering would be at 90 degrees from the incident beam, and the energy of the scattered beam would be much higher. This basic arrangement will work at energies up to 4 MeV – the standard maximum energy for inspection of the army's largest artillery rounds, though the shielding requirements will differ in material and thickness as a function of incident x-ray energy spectrum. There is always a trade-off between protective glass thickness, transmission, and resolution.

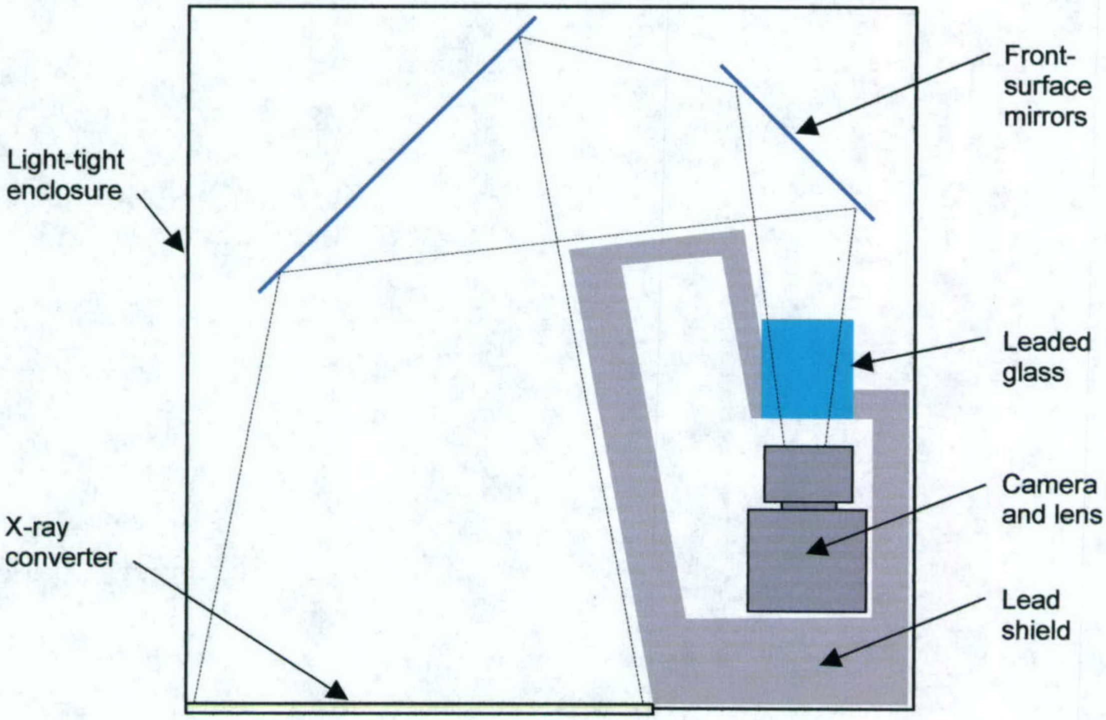


Figure 1. The basic layout (as seen from above in this context) of a two-fold XIM mirror design, where the optical and electronic components are shielded from all direct and all singly scattered x-rays. The leaded glass need stop only those doubly scattered x-rays and those whose scattering angle totals approximately 180 degrees from the incident beam direction. These latter x-rays have a much lower energy, and hence the leaded glass is a very effective protector of the interior rad-sensitive components. The camera must be sensitive to the edge-to-edge variation, where the edge-to-edge direction is perpendicular to the plane of the paper. XIM units would stack out of the paper, all overlapping slightly the adjacent unit.

Key features of the design include the now-familiar two-mirror double-folded optical path, which allows the CCD imager to face away from the beam direction. Thus, any singly-scattered x-rays will have a maximum energy of 250 keV. Doubly scattered x-rays [for which the flux is much, much lower] will have a maximum energy of 500 keV. Triply or higher-order scatterings are simply too sparse to count, and the calculations leading to expected flux levels are unreliable, owing to so much occurring in the local environment, e.g., how close a wall or other permanent fixturing is.

A fortuitous new product allowed us to use a much higher spatial resolution CCD camera than what we had previously used. The Santa Barbara Instruments Group ST2000XM camera has a 1200 x 1600 pixel CCD that is very sensitive to the blue-green phosphor of the intensifying screen. The camera is very low noise, and the thermal and readout noise is quite low. This camera allows full resolution over the 155 mm round, though as we mentioned previously, it is unlikely that we would use the XIM in that manner in a production manner. It turns out that with this camera, we can use a single Nikon 55 mm f/1.2 lens to do all the imaging that we had intended. In particular, there appears to be no need to use the 85 mm lens (the next higher standard size lens in focal length) to get the spatial resolution of 4 lp/mm (optical only).

For scatter-reduction in the experiment, our plan employs a thin-lead sheet located at the exit side of the x-ray beam from the test specimen. We also include some high energy grid experiments,\. While designed for lower energy x-rays than 2-4 MeV that we intend on using, any scatter would be markedly reduced because most of the scattered x-rays have energies that are well below 1 MeV.

In addition to the design of a single XIM module, we have produced several design concepts for covering large fields with a multi-XIM-unit approach. The next several figures show the basic XIM optical module.

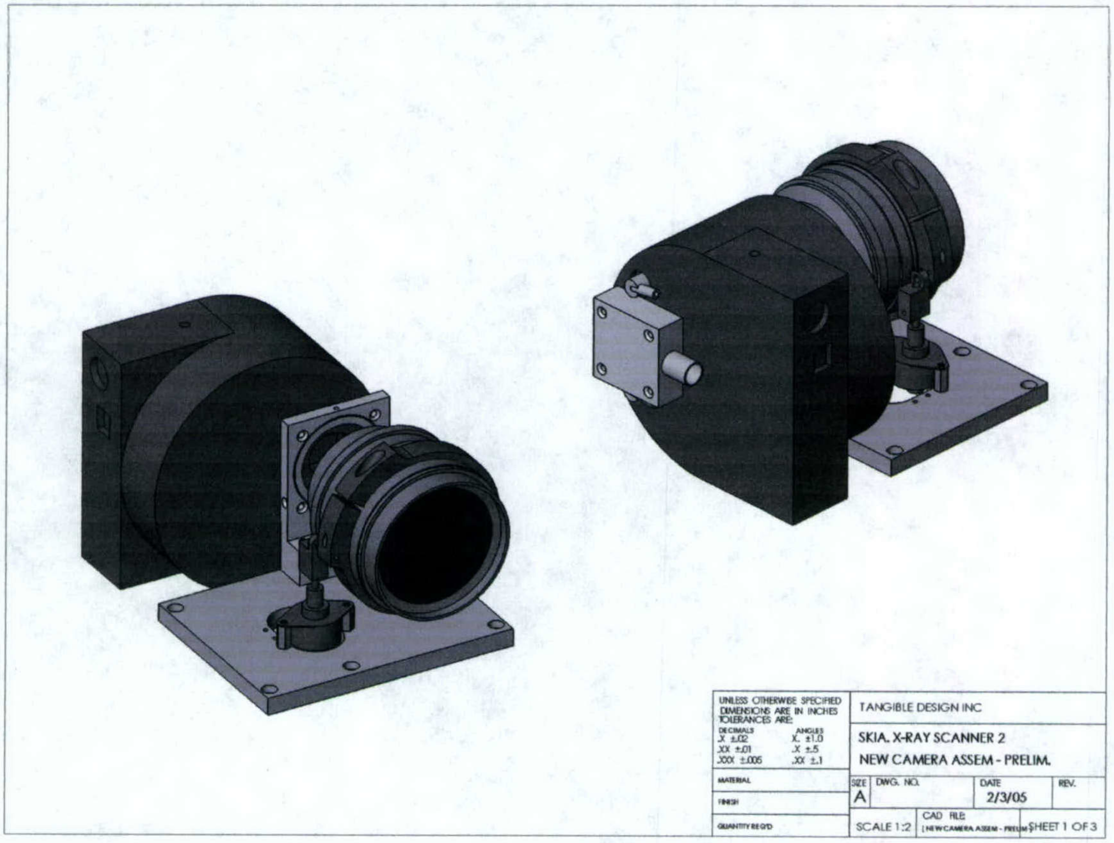


Figure 2 The X-ray lens and optical camera assembly inside the shielded box of figure 1.

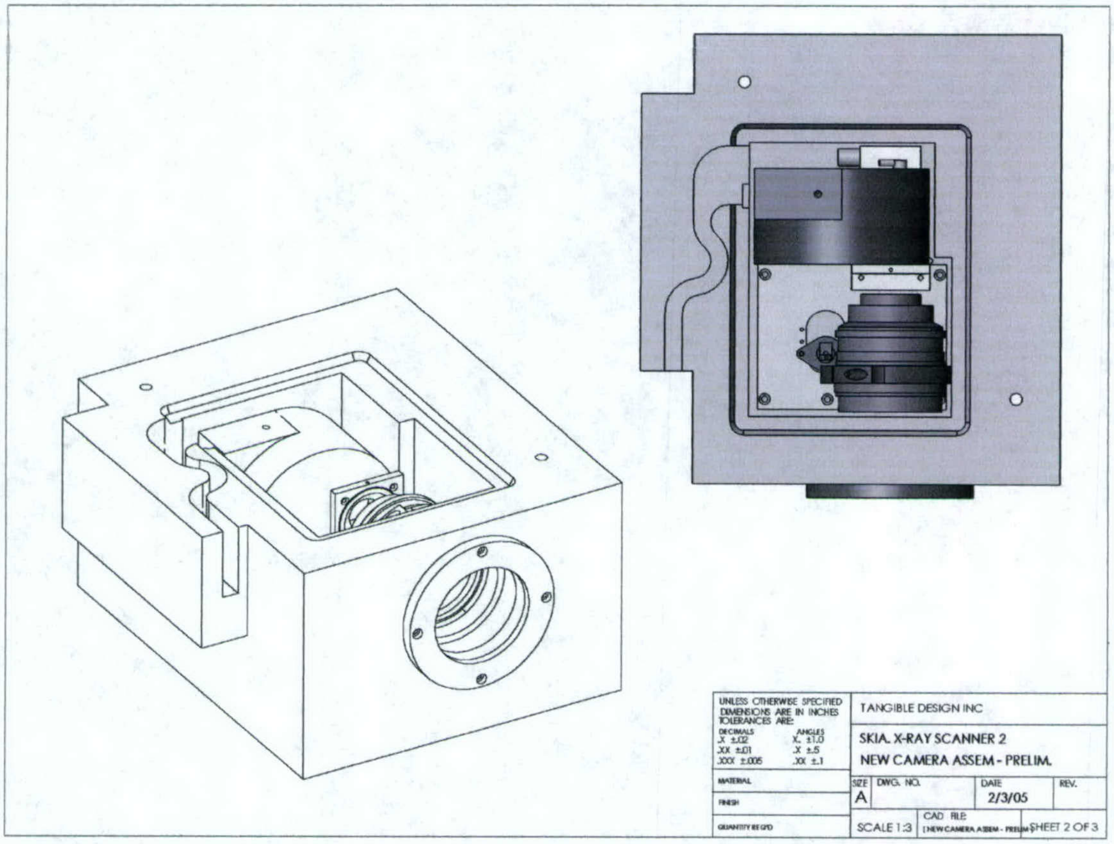


Figure 3 The leaded box shielding assembly that protects the CCD and optics from scattered x-rays. This was the actual as-built configuration for our test camera.

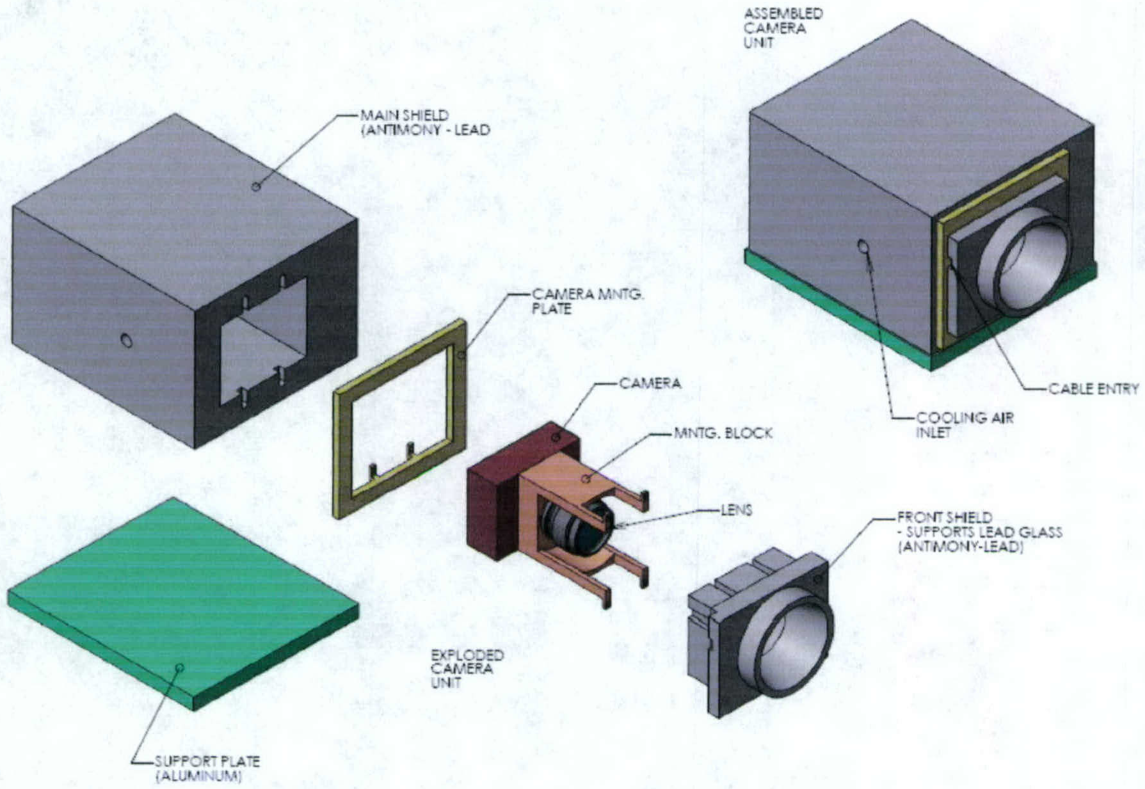


Figure 4 The inside of the XIM imaging unit consists of a CCD camera housed in an x-ray shielded box. The shielding also utilizes a leaded glass window that keeps backscattered x-rays out of the CCD electronics.

The next several figures show various layouts for multi-XIM units, depending on the configuration required.

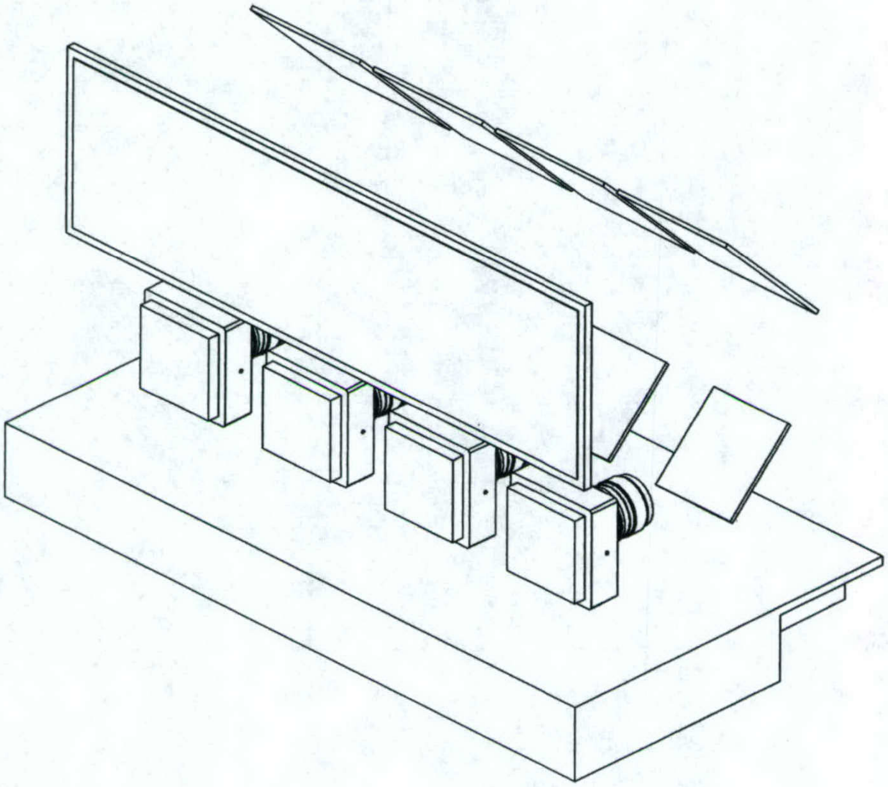


Figure 5 This configuration shows schematically how four XIM units might be arranged for examining a 48 inch long x 12 inch high field.

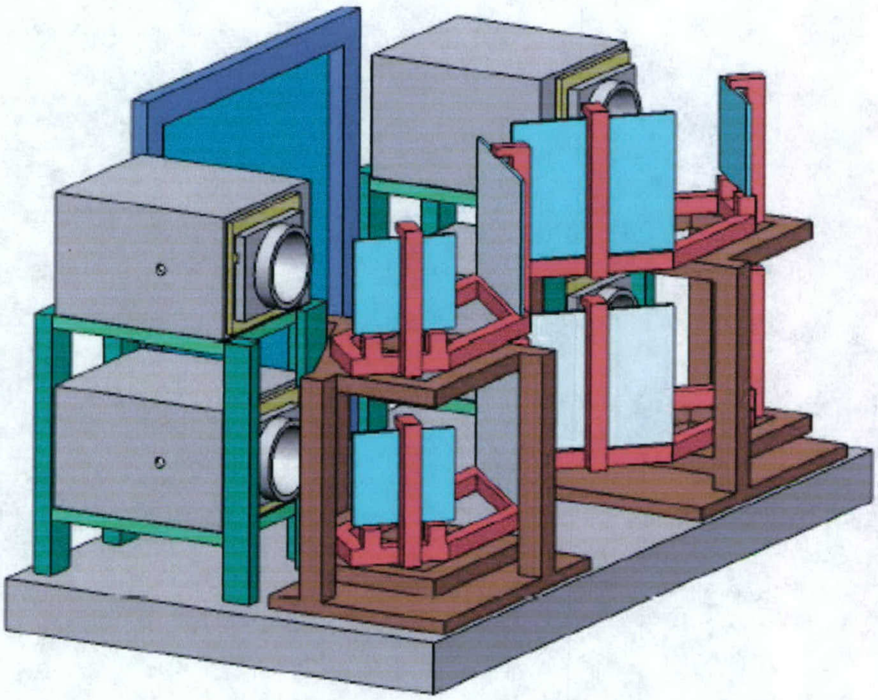


Figure 6. The 2 x 2 design for the 4-XIM x-ray imager. This is only one of a number of different configurations that can be assembled using the erector-set approach that is deliverable under phase II of this program. Each of the 4 XIM cameras looks at a 12 x 12 inch field on the 20 inch wide x 24 inch high scintillating screen. The individual XIM fields of view overlap slightly, so that a single large image x-ray image can be generated. (The 20 inch width of the scintillating screen is the limit for the current standard manufacturing machinery. A larger width could be procured, but that is a custom manufacturing job.)

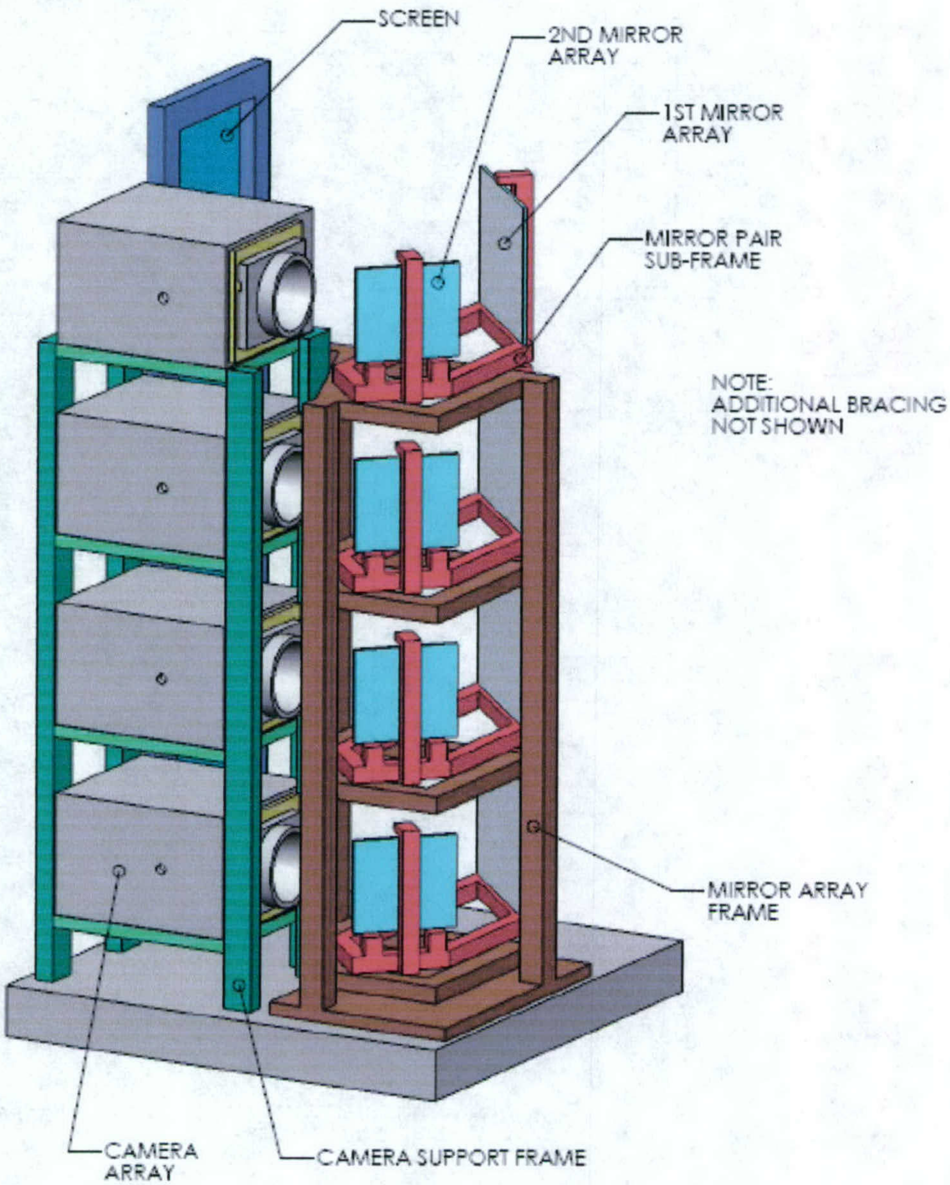


Figure 7. The 4 x 1 design for the 4-XIM x-ray imager.

B.3. Building the XIM unit

We built the entire unit and had it ready for delivery in three months after receipt of contract. The CCD camera, tested with visible light, conforms to its specifications, being able to deliver spatial resolution consistent with its pixelization. One of the truly serendipitous findings is that no external cooling seems to be required for operation at room temperature [20 degrees Celsius]. Noise also is as advertised in the camera specifications, approximately 8 electrons per pixel. (In fact, the camera does not seem to need even its internal cooling turned on for short exposures!) While we hope to be able to utilize the CCD camera with no extra external cooling, we did include cooling ports should they later prove necessary.

The entire XIM unit is controlled by a $600 Dell Inspiron 1000 laptop utilizing its USB 2.0 port. In fact, the USB cable is the only cable that runs from the control room to the XIM.

Software for readout has been accomplished, and the preliminary results have been readable by the NDEViewer, the JDLL quantitative image analysis software.

B.4. Assembly and test of the XIM unit onsite at Picatinny Arsenal

We completed and assembled the XIM unit at Picatinny Arsenal building 908 on April 11 and 12. The XIM unit was placed in the 2 MeV linac facility for testing.

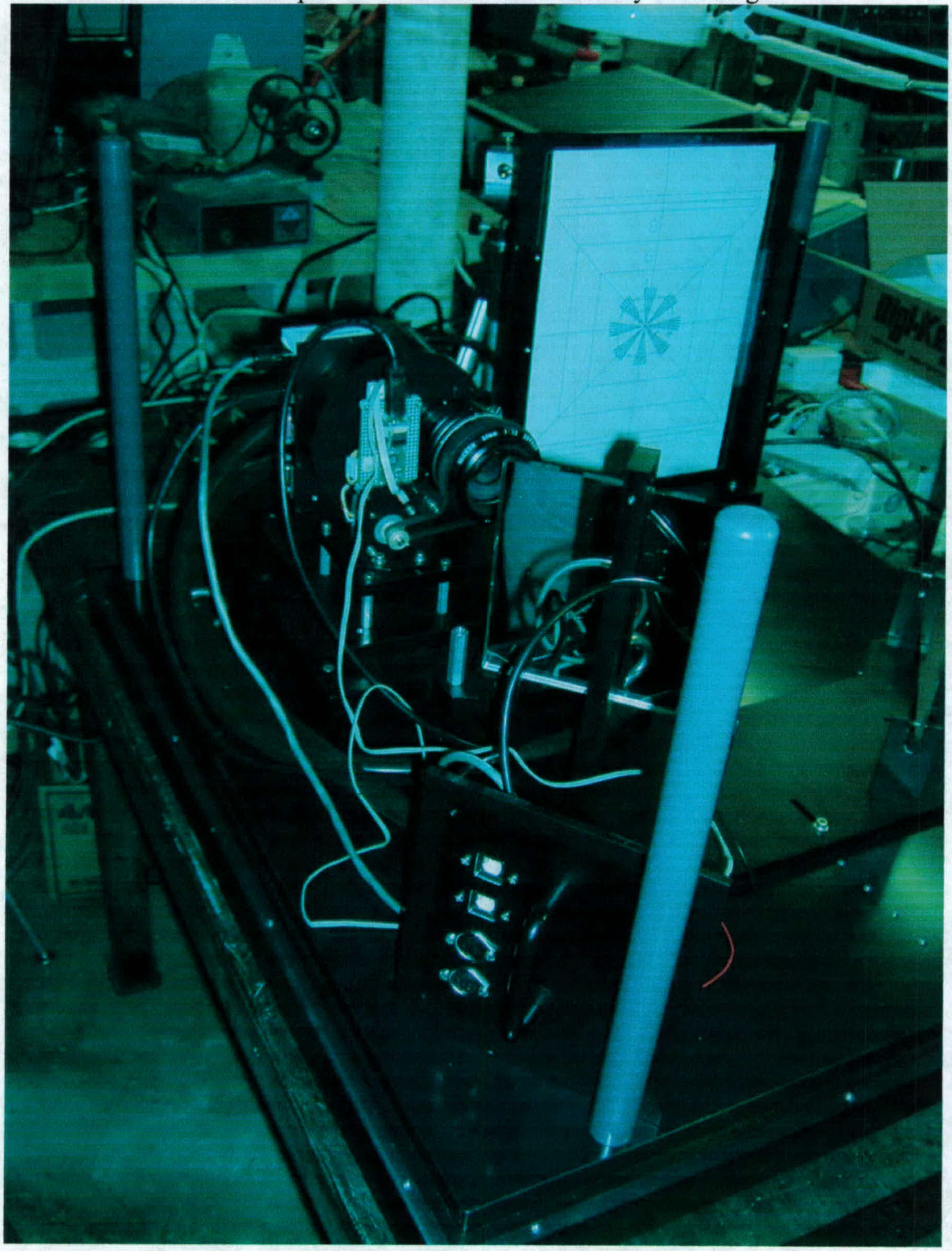


Figure 8. A picture taken during optical testing of the prototype XIM unit.

B.5. X-ray test at Picatinny and analysis of results

Initial tests at Picatinny include imaging with x-rays at energies generated by the 2 MeV Linatron. The Linatron was set up for operating in the panoramic mode, and so the flux at the conversion screen was approximately 6 R/minute, down by a factor of about 8 from where we would normally run with this source in the usual, non-panoramic mode. This is the energy range covered under the phase I program. Our more mundane tests included the following:

- Spatial resolution at center and at corners of array: the optical spatial resolution was consistent with the 4 lp/mm, which is the pixelization limit at the XIM conversion screen. The x-ray spatial resolution as measured across a boundary was consistent with the pixelization of the screen and the geometric unsharpness of the source (2 mm); the high energy scattering did not seem to add a significant degradation to the edge response function.
- Contrast was much better than in typical film photographs.
- Dynamic range was much better than in typical film radiographs. In particular, several objects that could not be film-radiographed in a single radiograph over their dynamic range were x-rayed with the XIM unit. A sample is shown in Figure 9.
- Noise / signal-to-noise measurements: consistent with 12.7 bits
- Line spread/point spread functions: consistent with geometric unsharpness.
- Coverage: for this prototype XIM, approximately 6 x 8 inches.
- X-ray-to-signal-out conversion efficiencies: for our first tests these were relatively inefficient because we did not have a lead converter sheet next to the scintillator. Our open field saturation times was about 10 minutes at a distance of 8 feet from the source, and using the highest possible spatial resolution. We expect this to improve significantly as we use different lenses and different conversion screens/combinations.
- The rough order of magnitude of direct hits into the CCD was 100/minute with the beam not being properly collimated. We estimate that this can be brought into the region of less than 1/minute with proper collimation, and the judicious use of a small bit of external shielding. Most of the direct hits originated in the direct beam hitting the aluminum baseplate and scattering into the CCD. By using tungsten in our next camera, this should be cut to much less than 1 direct hit per frame, which is desirable for quantitative reconstructive 3D imaging.
- In addition, demonstrations of remote focusing and readout control were conducted.

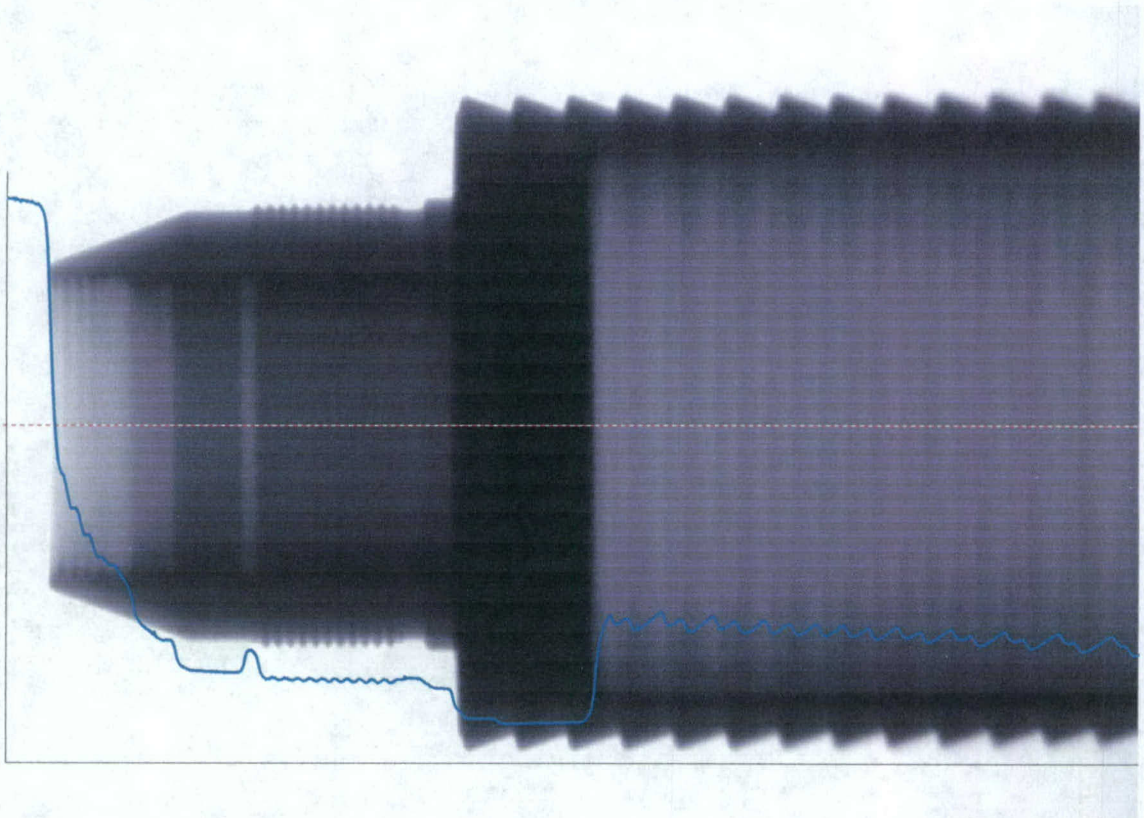


Figure 9. Image of M830 casing taken with 2 MeV x-rays. The x-ray density profile (in blue) is displayed along the axis (in red/white). All features of the casing can be seen on this *single* exposure, including not only obvious features like the front and back of the screw threads, but also the subtle features inside the throat. Note particularly the smoothness of the profile in the most heavily absorbed region, an area very difficult to see in conventional film.

We also demonstrated the ability to stitch together two overlapping areas with only slightly differing fields-of-view, but skewed alignments. We previously developed a similar technique for the Universal CT system that we developed for Picatinny. The difference here is that instead of simply mapping the field, as we did on UCT, we are meshing two different, but overlapping views. This was accomplished by the following technique:

- An exposure is made of a machined tungsten calibration mask that covers the entire area to be stitched together in x-rays.
- The CCD camera body is moved slightly, about an inch, so that there is no correlation between the current and previous camera position.
- Another exposure is made.
- From the first image we retain the left half plus a small region right of center. From the second image we retain the right half plus a small region left of center. The middle regions from each image become the overlap region, and we match both to the image of the machined calibration mask, which provides a coordinate transformation grid. In this way the overlap can be easily confirmed, the combined image can be aligned in software, and a final complete seamless image

can be produced. This provides experimental confirmation of the technique in x-rays, which can be applied to two completely independent CCD cameras.

- We accomplished this on XIM with the calibrated hole plate from UCT. This plate is a 0.100 inch thick lead alloy plate with a two-dimensional array of half inch holes placed on 1.0 inch centers.
- The details of the procedure:
  - Divide each hole image by its corresponding open image
  - Estimate and apply a geometric correction to each image so that the holes are all aligned and regular
  - Cut the two geometrically-corrected images at the same place (along a vertical line) and combine opposite halves from both images into a single image
  - Save the combined result as a TIFF image. The result is in the next figure, the top of which shows the badly joined data, while the bottom shows a well-engineered stitching. (An imaging expert could not distinguish the joining line, even with data profiling tools.)

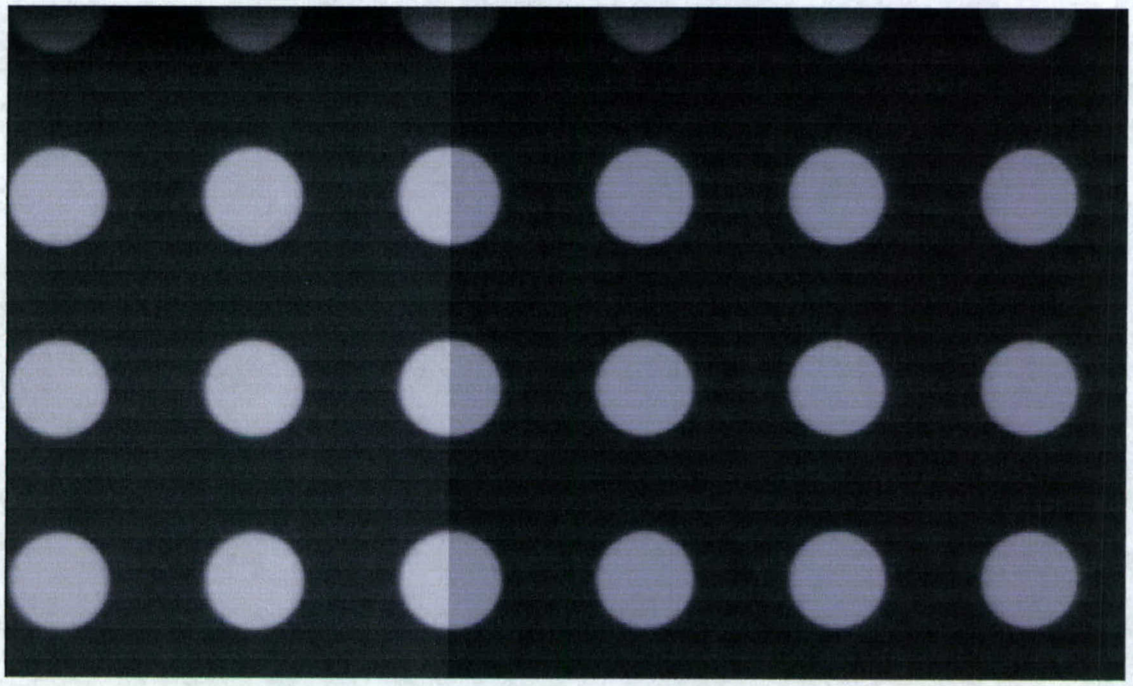
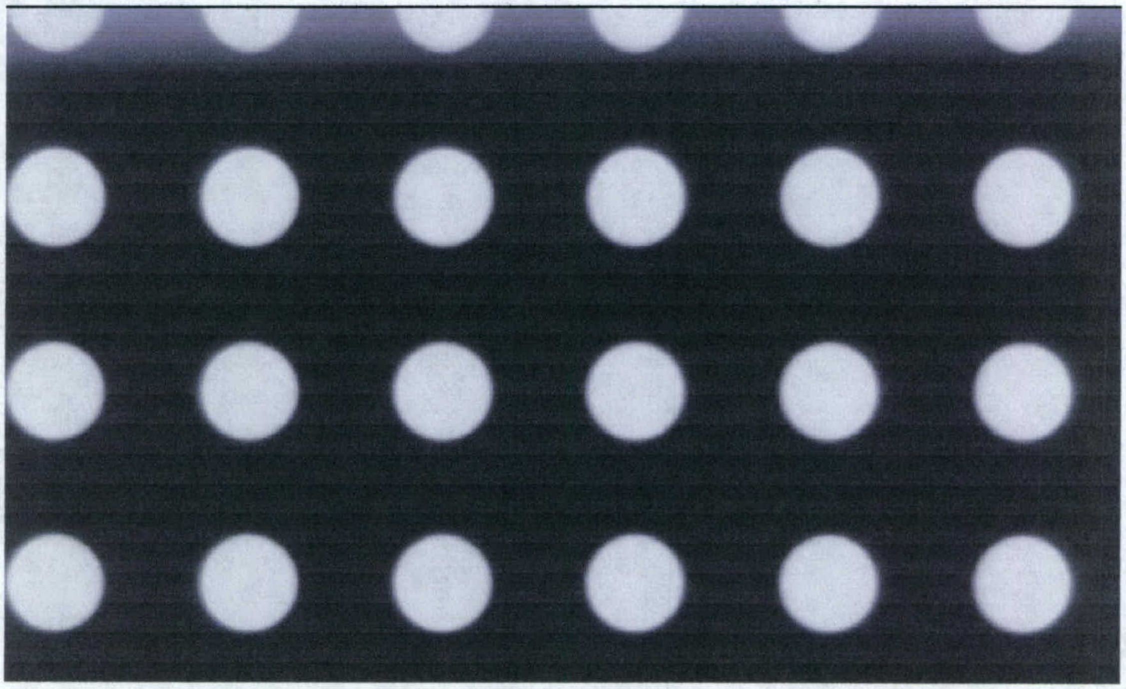


Figure 10 (a) The two individual projections have been shown clipped and butted together. Note the different intensity scale of each. More subtle are the geometric distortions, also not corrected here.



(b) Here, the two projections have been normalized, geometric distortions have been corrected, and the parts have been stitched into a single projection. The junction is in approximately the location where the two images join in (a).

In addition to these tests, we performed another series of tests involving a one-dimensional x-ray scatter-rejection grid. For operation at these energies, our anti-scatter grid was quite thick – half an inch along the beam direction. The grid consisted of strips of tungsten, 0.005 inch horizontally, interspersed with 0.093 inch plastic, as shown in the next couple of figures. The grid was aligned to the beam direction, with enough angular separation between the strips, so that, given the geometry of the set-up, there was no overlap of tungsten strips along any line of sight from the source to the detector. (Ideally, the strips would have been aligned along a focused arc pointing to the source, but this would have been difficult and expensive to accommodate on a short-term schedule and limited budget.) The idea is that most non-interacting x-rays pass through the plastic directly. Some of these non-interacting x-rays would be absorbed by the tungsten, but this would result in a definite pattern. Previously stored images of the grid could be used to normalize the image of an object taken this way. However, scattered x-rays would not travel along paths mostly normal to the surface; they are of lower energy and would be preferentially absorbed by having to travel through more tungsten than the straight-through x-rays.

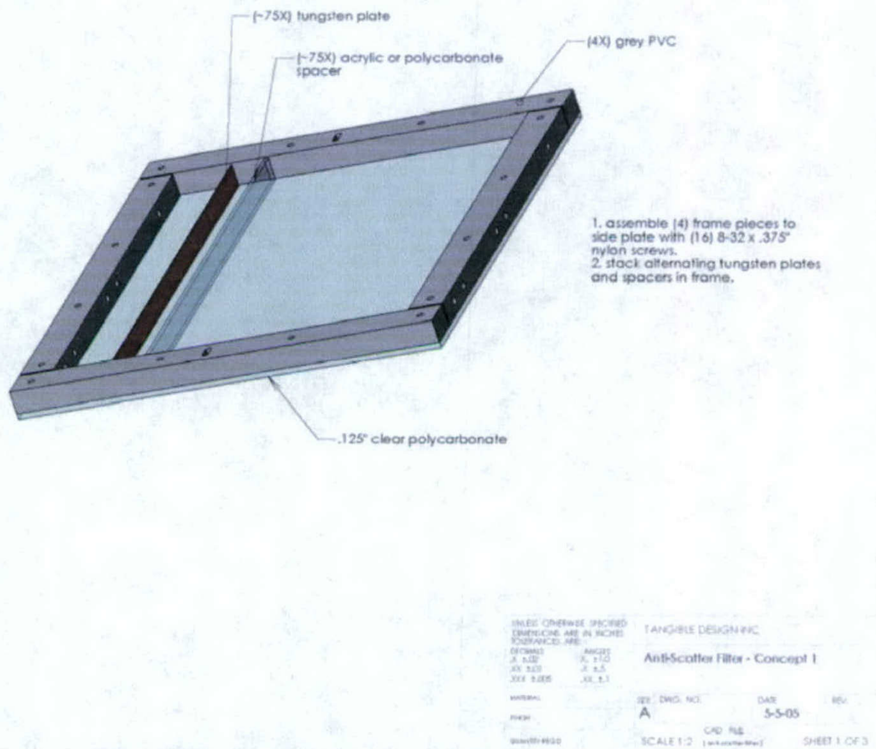


Figure 11 Components of the 1-dimensional grid assembly. The design was chosen so that when aligned at the proper distance from the source, most of the non-scattered x-rays would proceed directly through the plastic. Some of these non-scattered x-rays would be absorbed in the tungsten strips. The resultant image could be normalized for the presence of the tungsten strips. However, scattered x-rays would most be scattered through an angle that would require them to go through much more absorption – through many tungsten layers and through much plastic.

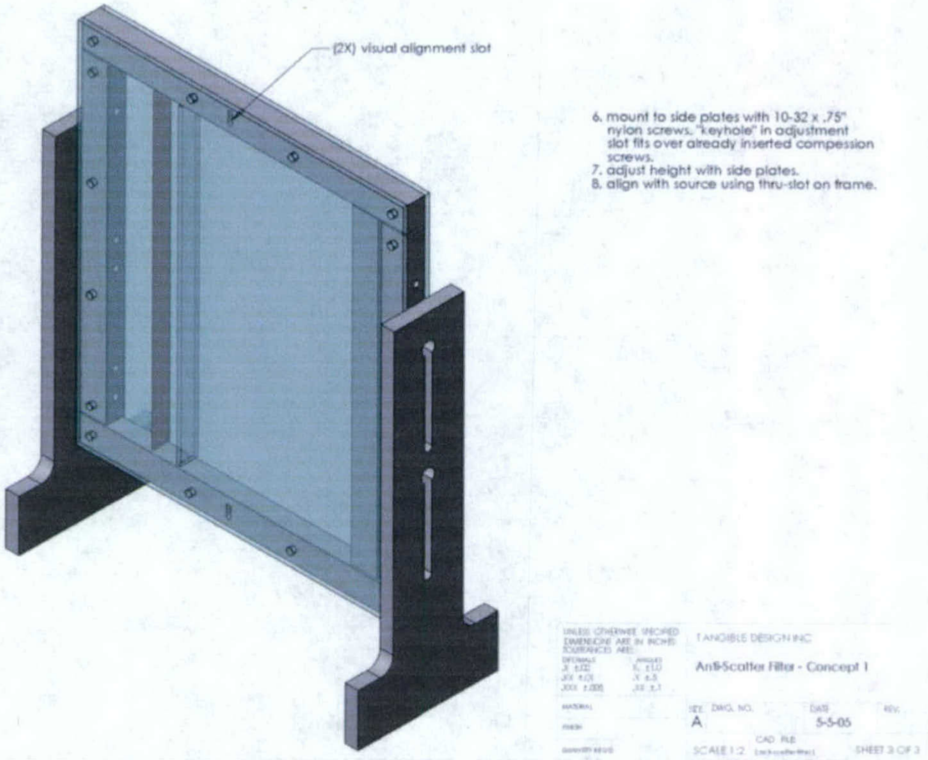


Figure 12 The assembled anti-scatter grid, which is adjustable in height, and rotational position.

We took several images of relatively absorbing objects, including an image of a base-separation phantom from a large Army ordnance sample, which is shown below.

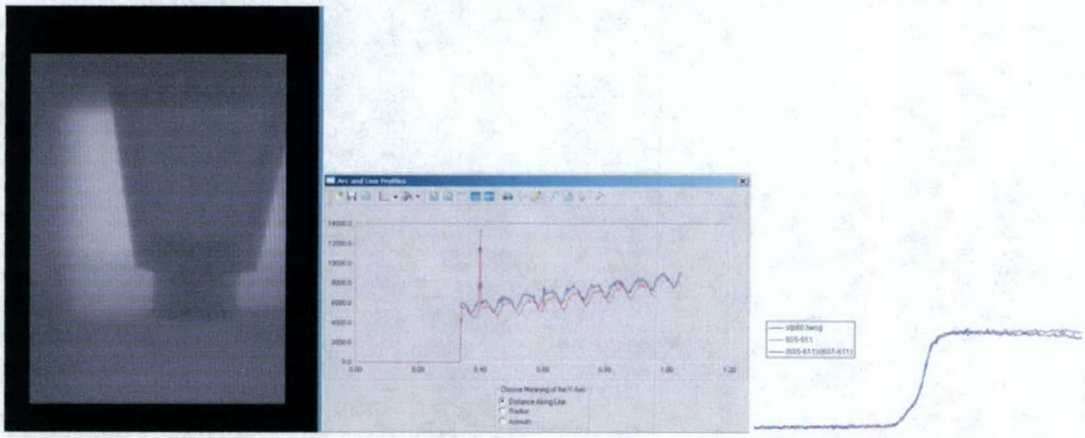


Figure 13 The leftmost image is of the phantom with the lines of the 1-dimensional tungsten grid showing vertically. The middle image is the normalized data of the grid vertical profile. (We have made corrections for slight misalignment of grid. The last image on the right shows three curves, all sitting on top of each other, showing profiles of gridless, grid-removed, and normalized grid-removed images There is no substantial improvement in scattering reduction.

B.6. Analysis of software tools

The last part of our phase I task was to perform an analysis of the software tools that we would need. There are three classes of such tools: those associated with simply getting a better image, e.g., the stitching of subimages together to make one grand canonical image, those software tools associated with processing the image data, e.g., reconstructive imaging from a series of projections, and those associated with everything else, e.g., mechanisms.

Configurable stitching over large, multi-XIM unit images

When multiple images comprise the measurement (in a multi-camera XIM), we extend the process described above, relying on the fidelity of a larger calibration plate to establish a common coordinate frame against which individual images can be offset and onto which they can be resampled. Clearly, absolute plate hole row and column numbers, as well as a boundary row or column must be determined in the region of image overlap to determine the image from which result samples are to be computed. The plate will be designed to facilitate this, and an automatic algorithm will take care of the details.

Software approach

The XIM design, with its configurable modules, invites flexible application. Likewise, we propose to provide a software toolkit that will encourage innovative use of the XIM in both projection reconstructive radiography applications. This will be accompanied with an application (e.g. cone beam CT, laminography, TDI, etc.) built using the toolkit.

A toolbox (with application) approach

We propose a toolkit consisting of one or more third-party off-the-shelf products augmented by our own custom additions. We currently expect that the products will include National Instruments' LabView (which provides excellent motion control and data acquisition using a variety of devices) and MathWorks' MATLAB (which provides well-thought-out data analysis). These products can interoperate and both provide rich, extensible environments for anything from ad hoc experimentation to application development. We will augment this combination with our own modules to enable acquisition from the multi-camera XIM.

Compatible viewer

All toolbox tools and the sample application will be compatible with the viewer (NDEViewer) currently associated with the Army's UCT system and its successor (DataProbe). In addition, data viewing tools associated with third party off-the-shelf components have data viewing tools that can be incorporated into designed applications or ad hoc experiments.

JDLL View Correction technology

Our toolbox will provide modules that access the functionality of JDLL's View Correction (VC) DLL (developed under a separate Army SBIR). This software library, originally intended for cone-beam CT preprocessing, contains a variety of algorithms useful to convert raw measured projections (with their numerous non-ideal characteristics) into ideal projections. This library greatly simplifies creation of better projection and reconstructive radiography applications. Our implementation will be consistent in design with conventions of the toolbox component it is intended to augment.

Sample application

In order to illustrate and validate our delivered toolbox, we will also deliver a simple radiographic application built using the toolbox. This application will include motion control, XIM acquisition, VC preprocessing, projection I/O, and some form of reconstruction or display processing using the toolkit.

C. Phase II Technical Objectives and Approach

Technical objectives listed here correspond exactly to like-numbered elements of the work plan in section D. This is the program plan for the next phase.

1. Confirmation of multi-MeV shielding approach: Further testing of the XIM prototype unit with complete shielding design at 2 MeV: The existing XIM design was executed with lead shielding. We need to complete the design in tungsten, which will yield final the best shielding in the smallest space. The phase I results to date have been very encouraging, but we need a final design confirmation.
2. Complete design for a full-up 4-XIM unit x-ray imager. Using our results from phase I as a basis, we learned that it is far more efficient to make separable boxes for each XIM unit rather than try to make a single large shielded box. This design would present an array of options. The configuration can be thought of as an erector set, which would allow the end-user a large number of choices, e.g., a if the XIM units are arranged vertically, the field would be 12 inches in width x 48 inches in height. If arranged in a square pattern, the field size would be 20[1] x 24 inches. This is possible because the scintillating x-ray screen is made in a continuous roll process. The important point here is that we can take all the data on a relatively large object in one swath.
3. Build the 4-unit XIM camera
4. Deliver the 4-XIM imager to Picatinny and test the camera with high energy x-rays in making stitched images. We will have to manufacture a large reference hole plate first, and use this to calibrate the 4 different fields-of-view of the cameras. Then it is a matter of stitching these images together.
5. Provide software tools for advanced x-ray reconstructive applications. These tools include the reconstructive imaging applications themselves and the associated mechanism control, calibration routines, and general geometry calculations that would allow large-scale conebeam CT, time-delay integration, and large area digital laminography to be accomplished.
6. Provide a complete reconstructive imaging application, e.g., CT, using the multi-XIM unit. Satisfying this objective would provide a complete end-to-end delivered system [except for the existing x-ray source] to the Picatinny Arsenal. Once this system is complete, these same tools could be used for other applications.

[1] The scintillation material is limited to 20 inches in width, though larger custom sizes are possible.

D. Phase II work plan

The work plan schedule is shown below. In phase I we showed that we can successfully image high energy x-rays over a wide dynamic range and with high spatial resolution. We have demonstrated stitching of images so that large areas can be imaged at once. In addition, we have shown a path that leads to greatly reduced scattering of x-rays into the x-ray imager itself, so that a greatly reduced number of "direct hits" were prevalent in the raw images. Phase II concentrates on building the 4-unit XIM, testing it with all the appropriate production software, and providing everything that's needed for a single soup-to-nuts application of advanced quantitative x-ray imaging reconstruction. In our case, that will be conebeam CT over large specimens.

Phase II Work Plan Schedule	**Months ARO**																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Task																								
Final experimental verification																								
Detailed design for 4-XIM unit																								
Software tools development																								
Build 4-XIM unit																								
Test 4-XIM unit at Picatinny																								
End-to-end reconstructive app.																								
Documentation																								
Final report																								

D.1. Final experimental verification

We will use the option program results to identify any further experimental tests that must be accomplished. This will employ an upgrade to the XIM prototype unit (Skiametrics owned, but on loan to Picatinny). Performance tests at Picatinny using existing XIM unit will be accomplished, including the use of scattering-reduction collimators that are to be delivered to Picatinny on a project for which JDLL, Inc. is prime.

D.2. Detail design for 4-XIM unit

First and foremost, flexibility is required in the Picatinny context. The reason is that the Picatinny quality group examines so many different specimens: some for nondestructive testing, some for quality engineering, some for classified investigations. We envision this set of XIM modules and associated hardware as the first of many different systems.

Skiametrics will provide:

- 4 XIM units. A XIM unit consists of one complete imaging unit, including scintillation screen, first- and second-fold mirrors, CCD camera and appropriate lens, housings and shielding material.
- Erector set fixturing pieces that allow flexibility so that different configurations, e.g., 2 x 2 and 1 x 4 modules are possible, and all other material (e.g., a very large scintillator) so that large images can be generated
- Calibration module
- Scatter rejection module [from JDLL implementations]
- Extra shielding/extra leaded glass as necessary
- Control computer and imaging software
- All necessary cables, interfaces, etc.

It is preferable for the XIM units to be constructed so that they can be configured in either left or right-mirrored configurations.

For the choice of CCD cameras, the most likely candidate will be fast camera available from SBIG. We need lots of pixels so that fine resolution can be available when we need it, but can bin data on-chip if we don't so that the readout time is not excessively long.

Almost all of screens emit in the 440-500 nanometer range, so blue sensitivity is important. All Kodak chips that we have been looking at have effective quantum efficiency in the 55% and above range here.

We will use a microlensed CCD, which is fine as long as effective f-number of system is not too small, i.e., f = 1.2 is ok. Luckily this is the standard Nikon lens that we have been using.

In order to get a larger field of view, we may slightly change geometry [rather than use shorter focal length lens].

The advantage of a larger field for individual XIM modules is that it allows the shielded CCD camera to be located further from the x-ray interaction volume. This configuration also allows more shielding to be interspersed if necessary. The CCD is also less susceptible to scatter by the usual 1/r-squared rules.

D.3. Software tools development

Configurable stitching

The key to successfully combining multiple XIM images into a single high-fidelity projection is extension of the Skiametrics's geometric correction process used in its UCT systems. In this process, a projection is acquired through a plate that contains numerous holes at known positions. The positions of these holes are accurately estimated. Offsets between the measured hole centers and the true hole center positions are used to generate a field of correction offsets that can be applied mechanically to each field acquired subsequently, correcting the geometric distortion field inherent in any lens system. This field of correction offsets is estimated only once unless the interior arrangement of imager elements has changed.

The algorithm described above requires precise normalization for intensity variations arising from exposure, dark current, vignetting, screen response variations, and beam profile. These operations are well-understood and can be applied with confidence, as the test case performed in this Phase I project illustrate.

Generalized stitching concept

When multiple images comprise the measurement (in a multi-camera XIM), we extend the process described above, relying on the fidelity of a larger calibration plate to establish a common coordinate frame against which individual images can be offset and onto which they can be resampled. Clearly, absolute plate hole row and column numbers, as well as a boundary row or column must be determined in the region of image overlap to determine the image from which result samples are to be computed. The plate will be designed to facilitate this, and an automatic algorithm will take care of the details. Since these are machined plates, standard machine-tool tolerances with optically based readouts – [1 part in 10,000] will be more than adequate over even the largest fields. We showed images of properly and improperly stitched images in the report of previous work accomplished.

Software approach

The XIM design, with its configurable modules, invites flexible application. Likewise, we propose to provide a software toolkit that will encourage innovative use of the XIM in both projection and reconstructive radiography applications. This will be accompanied with an application (e.g. cone beam CT, laminography, TDI, etc.) built using the toolkit.

A toolbox (with application) approach

We propose a toolkit consisting of one or more third-party off-the-shelf products augmented by our own custom additions. We currently expect that the products will include National Instruments' LabView (which provides excellent motion control and data acquisition using a variety of devices) and MathWorks' MATLAB (which provides well-thought-out data analysis). These products can interoperate and both provide rich, extensible environments for anything from ad hoc experimentation to application development. We will augment this combination with our own modules to enable acquisition from the multi-camera XIM.

Compatible viewer

All toolbox tools and the sample application will be compatible with the viewer (NDEViewer) currently associated with the Army's UCT system and its successor (DataProbe). In addition, data viewing tools associated with third party off-the-shelf components have data viewing tools that can be incorporated into designed applications or ad hoc experiments.

JDLL View Correction technology

Our toolbox will provide modules that access the functionality of JDLL's View Correction (VC) DLL (developed under a separate Army SBIR). This software library, originally intended for cone-beam CT preprocessing, contains a variety of algorithms useful to convert raw measured projections (with their numerous non-ideal characteristics) into ideal projections. This library greatly simplifies creation of better projection and reconstructive radiography applications. Our implementation will be consistent in design with conventions of the toolbox component it is intended to augment.

Sample application

In order to illustrate and validate our delivered toolbox, we will also deliver a simple radiographic application built using the toolbox. This application will include motion control, XIM acquisition, VC preprocessing, projection I/O, and some form of reconstruction or display processing using the toolkit.

D.4. Build 4-XIM unit

We will order all parts at once. We will assemble one module quickly so that we can run a test on that unit. We will take that unit to Picatinny as quickly as possible to run such tests. We will then analyze results; assuming that results are consistent with predictions from original XIM prototype unit, we will continue and assemble the other XIM units.

The technical monitor at Picatinny will choose an initial configuration of the erector set XIMs.

We will deliver and assemble the erector set on a moveable cart, so that the multi-unit XIM can be moved into and out of position as necessary. On our work with the XIM prototype unit of phase I we found that the installation of the unit on a cart greatly facilitated testing at the laboratory, because of the lack of continuous availability of x-ray facilities. The XIM camera could be moved into and out of the x-ray beam at a moment's notice.

D.5. Test at Picatinny

X-ray tests at Picatinny include imaging with x-rays at energies below 450 keV and those in the range of 450 keV to 2-3 MeV, depending on the availability of the x-ray sources at Picatinny.. Our more mundane tests include the following:

- Spatial resolution at center and at corners of array
- Contrast
- Dynamic range
- Noise / signal-to-noise measurements
- Line spread/point spread functions as necessary

- Coverage
- X-ray-to-signal-out conversion efficiencies

Each set will be accomplished at low and high x-ray energies. In addition, demonstrations of remote focusing, readout control (so that TDI, laminography, and other techniques requiring relative motion/coordination between XIM, test specimen, and source can be implemented), and overlapping fields-of-view will be conducted.

The ability of the combined 4-XIM unit to stitch together the two-to-four slightly overlapping areas to make a single ueber-image will be tested. The technique utilizes a large tungsten or lead alloy calibration plate:

- An exposure is made of the machined tungsten or lead-alloy calibration plate that covers the entire area to be stitched together in x-rays. The calibration plate consists of a 0.1-0.2 inch thick flat plate with half-inch diameter holes machined onto 1 inch centers.
- The image of each XIM unit is normalized and geometrically warp-compensated so that the images can be stitched together over the entire calibration plate area. The result is saved in a correction matrix for each XIM unit.
- The corrections matrix for each XIM unit is saved.
- The image of any test specimen is now acquired on all 4 XIM units, the corrections matrices applied, and a resultant composite image is generated.

We have already demonstrated that the camera responds to high energy pulsed x-rays with no "shuttering effects," common with mechanical shutters. [this is a major reason why we have chosen a CCD with an electronic shutter.]

Our experiment plan also utilizes the x-ray scatter reduction grids being manufactured currently under subcontract to JDLL on their CT artifact reduction program. The addition of these scatter reduction grids should substantially improve the finished x-ray shadowgraph images; moreover these processed images are used as inputs to the reconstructive imaging data applications like CT and TDI. Those applications should also be substantially improved.

We discuss scatter-reduction grids first from a low-energy perspective, and then from the high-energy viewpoint: Implementation of conventional low-energy scatter reduction grids is done in one of two ways. The grids cast a shadow of high spatial-frequency onto the detector. In the case of a stationary grid, this shadow must be very carefully subtracted; otherwise, high spatial frequency artifacts will absolutely dominate the image. The second approach oscillates the grid in a plane perpendicular to the beam, across the field of view over the course of each exposure, thus averaging the effects of the collimator over all pixels; the effect of the collimator must still be subtracted, but if the oscillation period is small compared to the exposure time, the relative effects of spatial frequency in the shadow of the grid on any single pixel are small, and hence, the errors in application of subtraction will be small. For the high energy approach we are considering here, the stationary approach is required for two reasons: First, in contrast to low energy grids, the collimator will be massive, 10-20 pounds at least, and oscillation will be difficult. Second, the high energy x-ray source is pulsed rather than continuous, and the combination of the oscillation and pulsing can create a beating effect on the image, which completely rules out certain exposure time ranges.

Analysis of these results will provide details as to how the application of the next section should be run. It is the quality of the initial two-dimensional shadowgraph x-ray image that directly affects the derived quantitative data images that we later extract.

D.6. An end-to-end application

A complete end-to-end application of a reconstructive x-ray imaging technique utilizing stitched, large-area x-ray images and software tools will be provided. A complete reconstructive imaging application will be provided to Picatinny. This will most likely be a CT or laminographic application and will entail providing a motion stage in order to move the specimen. ***CT is an ideal application for artillery rounds that the Army has difficulty inspecting in other ways. In particular, we expect that the combination of the four-unit XIM, the anti-scatter collimator, the JDLL software application tools, and the JDLL artifact reduction approach (funded under a current phase II SBIR program), should result in the best CT images ever constructed in this energy range.***

D.7. Documentation

Documentation for understanding, using, and fixing XIM will be generated and turned over to Picatinny. Documentation includes

- Mechanical and electrical drawings
- Assembly drawings that we have generated for the project
- Drawings provided by manufacturers of components
- Operations and maintenance manuals for OEM-providers
- Calibration and test procedures for XIM
- Operations and maintenance manuals for the XIM units and other hardware that we have provided
- Theory of operation and flow for implementation of XIM, particularly emphasizing data flow.
- List and contact information for third-party provided materials.

D.8. Final Report

A draft final report will be submitted at least 8 weeks prior to the end of the program. After revising according to technical monitor's comments we will submit final report at the end of the program. A final meeting and presentation will also be held at Picatinny at that time.

E. Acknowledgements

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